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Glass Color Standards and a Uniform Chromaticity Scale for Sugar Products*

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Color specifications for the official glass color standards of the U. S. Department of Agriculture for extracted honey, maple sirup, sugarcane sirup, and sugarcane molasses are presented. These standards are used for rapid classification of samples according to chromaticity. The chromaticities of the standards are widely and irregularly spaced along the sugar products locus on the CIE chromaticity diagram. Continuous single-number scales for color used in the sugar industry are based either on absorption measurements at specified wavelengths or on small-difference colorimetry. The uniform color scale of "NBS units of sugar color," proposed by Deitz and based on the Adams color-difference formula, is useful as presently formulated only for the lighter colors. In the present paper a greatly extended scale of uniform chromaticity, based on MacAdam's data, is presented for application to solutions of sugar products. Loci of points on the CIE diagram differing from the achromatic point by 5, 10, 15, ···, 220 units of chromaticity difference are established, and their intersections with an average locus of sugar products are determined. Forty-five glass color standards having chromaticities close to these intersections and thus spaced 5 units apart on the scale are described. The number of MacAdam units of sugar chromaticity, ΔS, for a given sample can be estimated by three methods: by interpolation between the aforementioned loci on the CIE diagram, if the chromaticity coordinates of the sample are known; by visual comparison with the 45 glass standards of known ΔS; and by measuring absorbancy of the sample at 420, 560, or 720 mμ and referring to graphs relating absorbancy to ΔS, if turbidity is negligible.

INTRODUCTION

No completely satisfactory or universal method has yet been developed for the rapid evaluation of the color and turbidity of sugar solutions in terms of one or two variables. Complications are presented by the wide range of chromaticities, by small but significant variations in the spectral character of the colorant, and by variations in the amount and character of suspended solids often present. Recent trends in the sugar industry are: a decreasing use of older visual comparison methods; an increasing use of one-dimensional photometric methods[1–4] involving measurement of absorption at specified wavelengths; and introduction of the NBS unit of sugar color[5] based on small-difference colorimetry. A fourth and specialized trend is the growing use of glass color standards for the classification of sugar products for regulatory purposes.

It is the purpose of this paper to review the present status of the Department of Agriculture's (USDA) glass color standards for several sugar products, and to present a single-number scale of uniform chromaticity for the evaluation of the color of sugar products over an extended range.

In the present paper the chromaticity aspect of sugar colors will be emphasized. For clarified solutions, the lightness attribute of color plays a minor role and can be considered dependent on chromaticity only, if observing conditions are properly adjusted. Excess turbidity due to suspended particles can be considered as a second variable and can be evaluated by separate methods, if important. Such methods will not be discussed. Official classification of the products under discussion is done on the basis of chromaticity only. When excess turbidity is present, it is roughly compensated so that attention can be confined to chromaticity comparisons.

GLASS COLOR STANDARDS

During the past ten years this Laboratory, in cooperation with the Agricultural Marketing Service, has developed glass color standards for the official classification of maple sirup, extracted honey, sugarcane sirups, and sugarcane molasses. In each case the standards are used for *classifying* samples of the product into broad groups according to chromaticity, which is one of the determining factors for grade of the product. These standards should not be thought of as providing a method of *determining* color; nor were they intended to replace, except for official purposes, methods of evaluation in use by the industry. They were developed to provide a simple, rapid, and convenient method of classification under conditions involving inspection of many samples in various locations.

The glass color standards for maple sirup and for extracted honey, adopted in 1950 and 1951, respectively, have been described.[6,7] The glass color standards for sugarcane sirup, designated No. 1, No. 2, and No. 3, are identical with three of the honey standards, namely, "White," "Extra light amber," and "Light amber." They were adopted in 1957[8] to replace colored solutions previously used.[9] They are shown in Fig. 1 mounted as

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7 Brice, Turner, and White, J. Assoc. Official Agric. Chem. **39**, 919 (1956).

8 "United States standards for grades of sugarcane sirup, effective April 16, 1957" (Agricultural Marketing Service, U. S. Department of Agriculture, Washington, D. C.).

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TABLE I. Specifications and colorimetric analysis of USDA glass color standards. CIE data are based on 1931 standard observer and Illuminant C.

	Liquid sugar[a]			Extracted honey						Maple sirup			Sugarcane sirup			Sugarcane molasses		
	Water white	White	Light amber	Water white	Extra white	White	Extra light amber	Light amber	Amber	Light amber	Medium amber	Dark amber	No. 1	No. 2	No. 3	No. 1	No. 2	No. 3
Thickness of product, mm	100	100	100	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	3.2	3.2	3.2	2.5	2.5	2.5
Glass type[b]	(1)	(2)	(3)	(2)	(3)	(4)	(5)	(5)	(6)+(7)	(8)	(9)	(9)	(4)	(5)	(5)	(5)	(5)	(6)+(7)
Glass thickness, mm	2.36	2.70	1.23	2.90	1.23	2.19	1.87	4.87	1.15+1.56	1.78	4.01	7.54	2.19	1.87	4.87	1.63	5.97	1.1+1.92
Tristimulus values $\times 10^{-3}$, X	79.747	71.535	Same as honey "Extra white"	64.854	62.974	51.411	38.120	15.700	3.161	48.886	31.160	15.420	Same as honey "White"	Same as honey "Extra Lt. amber"	Same as honey "Light amber"	41.362	11.539	2.068
Y	83.242	74.660		67.656	64.111	48.662	31.905	9.830	1.545	44.555	24.358	10.065				35.823	6.758	0.965
Z	72.887	43.430		37.372	23.951	7.337	1.674	0.035	0.005	5.381	0.453	0.039				2.619	0.015	0.002
Chromaticity coordinates, x	0.3381	0.3772		0.3818	0.4169	0.4786	0.5317	0.6141	0.6711	0.4947	0.5567	0.6041				0.5183	0.6301	0.6815
y	0.3529	0.3937		0.3982	0.4245	0.4531	0.4450	0.3845	0.3279	0.4509	0.4352	0.3943				0.4489	0.3691	0.3179
Luminous transmittance, %, T_c	83.2	74.7		67.7	64.1	48.7	31.9	9.83	1.54	44.6	24.4	10.07				35.8	6.76	0.96
Dominant wavelength, mμ, Λ	573.9	575.6		575.8	577.8	580.5	585.2	597.4	612.0	582.1	587.7	595.4				583.9	600.8	615.7
Excitation purity, %, P	17.4	38.8		41.2	57.0	81.9	93.9	99.7	99.8	85.5	98.0	99.7				91.4	99.9	99.9
NBS units of sugar color, ΔE_{NBS}	23.3	46.3	67.7	49.7	67.7	...	...	...	...	...	...	...	...	...	...	...	...	...
MacAdam chromaticity units, ΔS	20.2	40.4	59.6	42.7	59.6	94.7	125	167	206	104	138	162	94.7	125	167	117	176	214
Abbreviation, Tables III and IV	WW(*ls*)	W(*ls*)	...	WW(*h*)	EW(*h*)	W(*h*)	ELA(*h*)	LA(*h*)	A(*h*)	LA(*ms*)	MA(*ms*)	DA(*ms*)	...	...	...	...	...	...

[a] Experimental standards, 1954.
[b] L. J. Houze Convex Glass Co.: (1) Antique amber No. 6, (2) Amber No. 253LT (1938), (3) Amber No. 253NS, (4) Amber No. 253MM, (5) Amber No. 66DK-M1, (6) Cherry No. ALH-4, (7) Medium smoke MM, (8) Amber No. 253DK, (9) Amber No. 66LT.

alternate windows in a simple metal comparator identical with that used for maple sirup and honey.[6,7] The viewing thickness for samples of sugarcane sirup, $\frac{1}{8}$ in. (3.2 mm), is, however, much smaller than that for maple sirup and honey (31.5 mm). The container for samples is a cemented rectangular cell of transparent plastic. The filled cell is placed in compartment 2 or 4 of the comparator and comparison with adjacent standards is made by viewing the comparator against a diffuse source of natural or artificial daylight. Because of the high clarity of this product no turbid suspensions[6,7] or clear "blanks" behind the glass standards are necessary.

The glass color standards for sugarcane molasses, adopted in 1959,[10] are mounted and used in a similar manner. The standards are designated No. 1, No. 2, and No. 3. The viewing thickness for this extremely dark product is 0.100 in. (2.5 mm), and the container is similar to that for sugarcane sirup (Fig. 1). Since samples of molasses show variations in turbidity, three achromatic suspensions of diatomaceous earth, identical to those used with the standards for maple sirup,[6] are provided as a means of adjusting the luminous transmittance of the standards in making final comparisons of chromaticity.

Experimental glass color standards for liquid sugar were prepared in 1954 but have not been adopted. They are of interest in the present discussion because of the light color of this product. The sample was contained in a 100-mm optical cell and viewed in close juxtaposition to the three glass standards. An artificial daylight source provided diffuse illumination for critical viewing. No blanks or cloudy suspensions were required because of the high clarity of the product.

The glass color standards for all these products are used in a similar manner. The glass standards are mounted as windows in compartments 1, 3, and 5 of the comparator. The sample, in a square bottle or an optical cell of the prescribed internal thickness, is placed between adjacent standards. Classification is done on the basis of chromaticity only, the glass standards furnishing boundary points for the grade intervals on a one-dimensional scale. For products

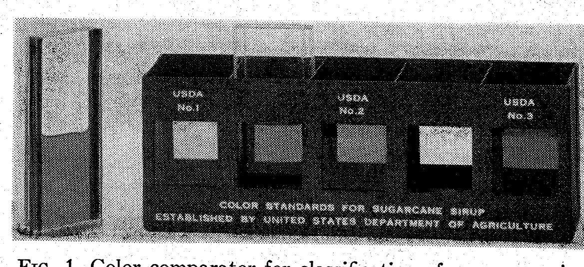

FIG. 1. Color comparator for classification of sugarcane sirup, showing the three mounted glass standards and two samples in cells of internal thickness $\frac{1}{8}$ in.

[10] "United States standards for grades of sugarcane molasses, effective November 16, 1959" (Agricultural Marketing Service, U. S. Department of Agriculture, Washington, D. C.).

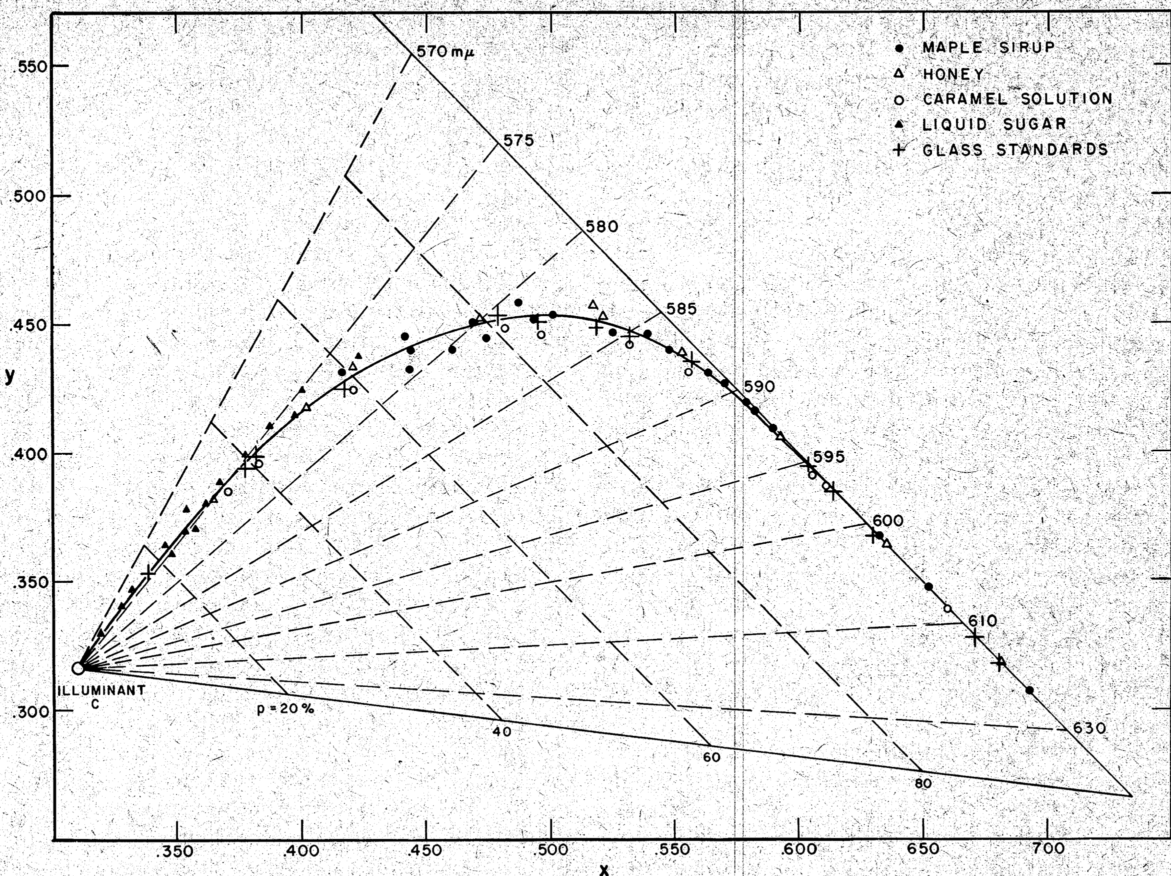

FIG. 2. CIE chromaticity diagram, showing coordinates for samples of maple sirup 31.5 mm (●); extracted honey, 31.5 mm(△); caramel-glycerin solutions, 31.5 mm (○); liquid sugar, 100 mm (▲); the various USDA glass color standards for sugar products (+); and the average locus of chromaticities for sugar products.

having variations in turbidity (maple sirup, extracted honey, and sugarcane molasses) clear "blanks" and achromatic suspensions of diatomaceous earth, in three levels of turbidity, are provided in 31.5-mm square bottles. The blanks or turbid suspensions are placed behind the glass standards in such a way that final comparison of sample chromaticity with standard chromaticity is made at roughly the same level of luminous transmittance using a diffuse source of natural or artificial daylight. The accuracy of classification is very high since only a small proportion of samples will have chromaticities close enough to the standards to make classification difficult or doubtful. Disputed classifications can, if necessary, be resolved in the laboratory using a polarization photometer, a source of CIE Illuminant *C*, a master set of standards, and a precision cell.

Complete specifications for the various glass color standards are assembled in Table I. Methods and tolerances have been previously described.[6,7] The accuracy of the CIE data for the two standards using red glass, type (6), is less than that for the other standards. Figure 2 is a plot of the CIE chromaticity diagram showing the coordinates of the glass color standards and of various samples, and an average locus of chromaticities of sugar products drawn through the sample points. The pattern is similar to that shown by Deitz[5] for other sugar products such as granulated, raw, and soft sugars in solution.

SINGLE-NUMBER CHROMATICITY SCALE

For the lighter and medium-colored products of Fig. 2 there is appreciable scattering of points about the average locus. The system is therefore not strictly one-dimensional in respect to chromaticity. The "off-locus" samples give rise to difficulty in any attempt to devise a single-number method of evaluating the chromaticity of these products, whether it be absorptiometric or visual. In such attempts two samples may have the same scale number but will look different visually. Another type of "off-locus" deviation, in another dimension, can be produced by variations in turbidity. The latter can be eliminated by dealing only with filtered solutions or by compensating the turbidity in some way.

In spite of these deviations, single-number scales of color are attractive and have found use in the sugar industry. There are two approaches in establishing such scales. One is physical, based on measurement of absorbancy or attenuancy at one or more wavelengths.[1–4] This measures approximate relative concentration of colorant. The second approach is psychophysical, based on visual discrimination data.

Deitz[5] has made a major contribution on the latter approach by introducing the "NBS unit of sugar color." This system expresses, on a scale of uniform perceptibility, the number of just noticeable units of color difference between a given sugar solution and a "colorless" reference solution of highly purified sucrose when viewed under CIE Illuminant C. This color difference, ΔE_{NBS}, is a fundamental quantity based ultimately on a large body of data associated with the Munsell color system through the Adams formula for computing small color differences. The number of NBS units of sugar color for a given sugar solution can be calculated precisely from tristimulus values or approximately from attenuancy[11] measurements at 420 and 560 mμ. The method applies very well in the region of lighter sugar colors for which it was designed. It cannot be applied, at least by the present method of calculation, to the medium and highly colored solutions shown in Fig. 2. This limitation was fully realized by Deitz and will be discussed later.

Other choices are available in the field of small-difference colorimetry.[12] In the following analysis, the data of MacAdam,[13] based on the standard deviation of chromaticity matching of aperture colors at constant luminance, have been applied to the problem in a fashion outlined by Ingle.[14] The MacAdam equation for the difference ΔS between two chromaticities is

$$(\Delta S)^2 = g_{11}(\Delta x)^2 + 2g_{12}\Delta x\Delta y + g_{22}(\Delta y)^2, \qquad (1)$$

where Δx and Δy are the differences in the CIE coordinates for the two chromaticities; and g_{11}, $2g_{12}$, and g_{22} are coefficients that can be determined by graphical interpolation.[13] Increments along a line of constant dominant wavelength in the CIE chromaticity diagram can be expressed by

$$\Delta y = m\Delta x, \qquad (2)$$

where m is the slope of the line, which can be readily calculated.[15] By eliminating Δy between Eqs. (1) and (2), and solving for Δx

$$\Delta x = \Delta S/(g_{11} + 2g_{12}m + g_{22}m^2)^{\frac{1}{2}}. \qquad (3)$$

This equation was used to compute by successive increments of $\Delta S = 5$ the coordinates of points along lines of constant dominant wavelength that differ from the achromatic point by 5, 10, 15, $\cdots$ MacAdam units of chromaticity difference. The numerous interpolations necessary were facilitated, and cumulative errors minimized, by the following steps: replotting MacAdam's Figs. 1–3 to a larger scale; superposing twelve lines of constant dominant wavelength from 570 to 620 mμ on each plot; plotting twelve curves each of g_{11}, $2g_{12}$, and g_{22} *versus* x from the intersections of the lines of constant dominant wavelength with loci of various values of the coefficients; determining, from the latter plots, the values of g_{11}, $2g_{12}$, and g_{22} corresponding to intermediate or average values of x for each successive interval $\Delta S = 5$ along a line of constant dominant wavelength; and finally, computing Δx and Δy for each interval from Eqs. (3) and (2), and from these values of x and y for each point corresponding to $\Delta S = 5$, 10, 15, $\cdots$ along each line of constant dominant wavelength.

The coordinates of the latter points are shown in Table II. The results are plotted in Fig. 3, showing the loci of points distant from the achromatic point by 5, 10, 15, $\cdots$, 220 MacAdam units, and the average locus of chromaticities of solutions of sugar products. This scheme furnishes a fundamental scale of uniform perceptibility along or near the average locus of chromaticities of sugar products, making it possible to express the departure from "colorless," along a line of constant dominant wavelength, for any given sugar solution. The value of ΔS, or "MacAdam units of sugar chromaticity," can be precisely determined by interpolation on this graph, if the chromaticity coordinates of the sample are known. This is true whether the sample is on the average locus of sugar products or is an "off-locus" chromaticity. Values of ΔS for the various USDA glass color standards for sugar products calculated in this way are shown in Table I.

A second method of determining ΔS for a given sugar solution would be available if we had a set of some 45 glass color standards representing the intersections, in Fig. 3, of the MacAdam loci with the average locus of sugar products. Each glass could be designated by 5, 10, 15, $\cdots$, 220 MacAdam units of sugar chromaticity. By visual comparison of a sample with these glass standards a value of ΔS could readily be estimated. A set of such glasses, corresponding approximately to the indicated intersections, has been prepared in accordance with the specifications in Table III. CIE data, and hence ΔS values, were available for at least three thicknesses of each glass type shown. This permitted use of a single-wavelength test method, similar to that already described,[6,7] for calculating the thickness of a glass type to give a specified value of ΔS. This was done from linear plots of ΔS *vs* transmittance relative to a standard T/T_s at selected wavelengths. The 45 glasses were mounted on frames in such a way that a sample could be moved along the series in close juxtaposition to the glasses. One or more clear glass sheets were combined with some of the glasses to adjust their luminous transmittances to approximately equal those of caramel-glycerin solutions (or filtered sugar solutions).

[11] Deitz, Pennington, and Hoffman, J. Research Natl. Bur. Standards **49**, 365 (1952).
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TABLE II. Chromaticity coordinates of points, along lines of constant dominant wavelength, differing from the achromatic point by 5, 10, 15, ··· MacAdam units of chromaticity difference, ΔS.

ΔS	570 mμ x	570 mμ y	572.5 mμ x	572.5 mμ y	575 mμ x	575 mμ y	577.5 mμ x	577.5 mμ y	580 mμ x	580 mμ y	585 mμ x	585 mμ y
0	0.3101	0.3163	0.3101	0.3163	0.3101	0.3163	0.3101	0.3163	0.3101	0.3163	0.3101	0.3163
5	0.3154	0.3257	0.3162	0.3252	0.3167	0.3243	0.3169	0.3231	0.3169	0.3220	0.3164	0.3200
10	0.3207	0.3351	0.3225	0.3344	0.3235	0.3325	0.3239	0.3302	0.3238	0.3278	0.3229	0.3238
15	0.3265	0.3454	0.3293	0.3443	0.3309	0.3414	0.3314	0.3378	0.3312	0.3340	0.3297	0.3278
20	0.3326	0.3563	0.3363	0.3545	0.3388	0.3509	0.3395	0.3460	0.3391	0.3406	0.3369	0.3320
25	0.3391	0.3679	0.3437	0.3653	0.3469	0.3607	0.3479	0.3545	0.3474	0.3476	0.3445	0.3365
30	0.3462	0.3805	0.3518	0.3771	0.3556	0.3712	0.3569	0.3636	0.3563	0.3551	0.3526	0.3413
35	0.3540	0.3944	0.3607	0.3901	0.3651	0.3827	0.3666	0.3734	0.3659	0.3632	0.3613	0.3464
40	0.3626	0.4097	0.3703	0.4041	0.3754	0.3951	0.3771	0.3840	0.3762	0.3719	0.3706	0.3519
45	0.3715	0.4255	0.3799	0.4181	0.3859	0.4078	0.3878	0.3948	0.3872	0.3812	0.3804	0.3577
50	0.3799	0.4404	0.3889	0.4312	0.3959	0.4199	0.3983	0.4054	0.3984	0.3906	0.3908	0.3638
55	0.3877	0.4543	0.3972	0.4433	0.4049	0.4308	0.4083	0.4155	0.4094	0.3999	0.4014	0.3700
60	0.3951	0.4675	0.4050	0.4547	0.4133	0.4410	0.4175	0.4248	0.4197	0.4086	0.4120	0.3762
65	0.4022	0.4801	0.4124	0.4655	0.4212	0.4505	0.4261	0.4335	0.4293	0.4167	0.4225	0.3823
70	0.4091	0.4924	0.4195	0.4759	0.4287	0.4596	0.4343	0.4418	0.4383	0.4243	0.4328	0.3884
75	0.4157	0.5041	0.4264	0.4860	0.4359	0.4683	0.4421	0.4497	0.4469	0.4315	0.4429	0.3943
80	0.4222	0.5157	0.4331	0.4958	0.4429	0.4768	0.4497	0.4574	0.4552	0.4385	0.4528	0.4001
85	0.4286	0.5271	0.4397	0.5054	0.4497	0.4850	0.4570	0.4648	0.4631	0.4451	0.4625	0.4058
90	0.4349	0.5383	0.4461	0.5147	0.4563	0.4930	0.4641	0.4720	0.4708	0.4516	0.4720	0.4114
95	0.4411	0.5493	0.4524	0.5239	0.4628	0.5009	0.4710	0.4790	0.4783	0.4579	0.4812	0.4168
100	0.4472	0.5602	0.4587	0.5331	0.4692	0.5086	0.4778	0.4858	0.4856	0.4640	0.4902	0.4221
105	0.4533	0.5711	0.4650	0.5423	0.4756	0.5163	0.4845	0.4925	0.4927	0.4700	0.4989	0.4272
110					0.4819	0.5239	0.4911	0.4991	0.4997	0.4759	0.5075	0.4323
115							0.4976	0.5056	0.5066	0.4817	0.5159	0.4372
120							0.5040	0.5120	0.5134	0.4874	0.5241	0.4420
125											0.5322	0.4468
130											0.5401	0.4515
135											0.5479	0.4561
140											0.5556	0.4606

ΔS	590 mμ x	590 mμ y	595 mμ x	595 mμ y	600 mμ x	600 mμ y	605 mμ x	605 mμ y	610 mμ x	610 mμ y	620 mμ x	620 mμ y
0	0.3101	0.3163	0.3101	0.3163	0.3101	0.3163	0.3101	0.3163	0.3101	0.3163	0.3101	0.3163
5	0.3159	0.3187	0.3156	0.3178	0.3153	0.3172	0.3151	0.3168	0.3150	0.3165	0.3148	0.3162
10	0.3219	0.3211	0.3212	0.3193	0.3206	0.3181	0.3202	0.3173	0.3200	0.3167	0.3196	0.3161
15	0.3280	0.3236	0.3269	0.3209	0.3260	0.3191	0.3254	0.3178	0.3250	0.3169	0.3244	0.3160
20	0.3344	0.3262	0.3328	0.3225	0.3316	0.3201	0.3307	0.3183	0.3301	0.3172	0.3293	0.3159
25	0.3412	0.3290	0.3390	0.3242	0.3374	0.3211	0.3362	0.3189	0.3354	0.3175	0.3343	0.3158
30	0.3484	0.3319	0.3455	0.3260	0.3435	0.3222	0.3419	0.3195	0.3409	0.3178	0.3395	0.3157
35	0.3561	0.3350	0.3524	0.3279	0.3498	0.3233	0.3479	0.3201	0.3466	0.3181	0.3449	0.3156
40	0.3644	0.3384	0.3597	0.3298	0.3565	0.3245	0.3542	0.3208	0.3526	0.3184	0.3505	0.3155
45	0.3731	0.3419	0.3675	0.3319	0.3636	0.3258	0.3608	0.3215	0.3589	0.3187	0.3563	0.3154
50	0.3822	0.3456	0.3757	0.3341	0.3710	0.3271	0.3678	0.3222	0.3654	0.3190	0.3624	0.3153
55	0.3918	0.3495	0.3842	0.3364	0.3787	0.3285	0.3750	0.3229	0.3722	0.3193	0.3688	0.3152
60	0.4018	0.3536	0.3930	0.3388	0.3867	0.3299	0.3825	0.3237	0.3793	0.3197	0.3754	0.3151
65	0.4119	0.3577	0.4022	0.3413	0.3950	0.3314	0.3903	0.3245	0.3866	0.3201	0.3822	0.3150
70	0.4221	0.3619	0.4116	0.3439	0.4036	0.3329	0.3984	0.3253	0.3941	0.3205	0.3892	0.3149
75	0.4324	0.3661	0.4212	0.3465	0.4125	0.3345	0.4067	0.3262	0.4019	0.3209	0.3964	0.3147
80	0.4428	0.3703	0.4310	0.3492	0.4216	0.3361	0.4152	0.3271	0.4099	0.3213	0.4038	0.3145
85	0.4532	0.3745	0.4410	0.3519	0.4309	0.3377	0.4239	0.3280	0.4181	0.3217	0.4114	0.3143
90	0.4636	0.3787	0.4513	0.3547	0.4404	0.3394	0.4328	0.3289	0.4265	0.3221	0.4191	0.3141
95	0.4739	0.3829	0.4618	0.3576	0.4502	0.3411	0.4420	0.3299	0.4350	0.3225	0.4270	0.3139
100	0.4842	0.3871	0.4725	0.3605	0.4602	0.3429	0.4514	0.3309	0.4437	0.3229	0.4350	0.3137
105	0.4943	0.3912	0.4834	0.3635	0.4704	0.3447	0.4610	0.3319	0.4526	0.3233	0.4432	0.3135
110	0.5043	0.3953	0.4943	0.3665	0.4809	0.3466	0.4708	0.3329	0.4617	0.3238	0.4516	0.3133
115	0.5141	0.3993	0.5052	0.3695	0.4916	0.3485	0.4809	0.3339	0.4710	0.3243	0.4601	0.3131
120	0.5238	0.4032	0.5162	0.3725	0.5025	0.3504	0.4912	0.3350	0.4806	0.3248	0.4685	0.3129
125	0.5334	0.4071	0.5271	0.3755	0.5137	0.3524	0.5018	0.3361	0.4904	0.3253	0.4777	0.3127
130	0.5429	0.4110	0.5379	0.3785	0.5251	0.3544	0.5126	0.3372	0.5004	0.3258	0.4867	0.3125
135	0.5523	0.4148	0.5486	0.3814	0.5366	0.3564	0.5237	0.3384	0.5106	0.3263	0.4959	0.3123
140	0.5615	0.4185	0.5592	0.3843	0.5481	0.3584	0.5350	0.3396	0.5210	0.3268	0.5053	0.3121
145	0.5706	0.4222	0.5698	0.3872	0.5596	0.3604	0.5466	0.3408	0.5317	0.3273	0.5149	0.3119
150	0.5796	0.4259	0.5803	0.3901	0.5711	0.3624	0.5584	0.3420	0.5427	0.3278	0.5247	0.3117
155	0.5885	0.4295	0.5907	0.3930	0.5825	0.3644	0.5704	0.3432	0.5539	0.3284	0.5347	0.3115
160			0.6010	0.3958	0.5939	0.3664	0.5825	0.3445	0.5655	0.3290	0.5450	0.3113
165			0.6111	0.3986	0.6052	0.3684	0.5947	0.3458	0.5773	0.3296	0.5555	0.3111
170			0.6211	0.4013	0.6165	0.3704	0.6069	0.3471	0.5893	0.3302	0.5663	0.3109
175			0.6310	0.4040	0.6276	0.3724	0.6192	0.3484	0.6014	0.3308	0.5774	0.3107
180					0.6386	0.3744	0.6314	0.3497	0.6135	0.3314	0.5887	0.3105
185							0.6435	0.3510	0.6257	0.3320	0.6002	0.3103
190							0.6555	0.3522	0.6380	0.3326	0.6119	0.3101
195									0.6503	0.3332	0.6238	0.3098
200									0.6626	0.3338	0.6358	0.3095
205									0.6749	0.3344	0.6479	0.3092
210											0.6601	0.3089
215											0.6724	0.3086
220											0.6848	0.3083

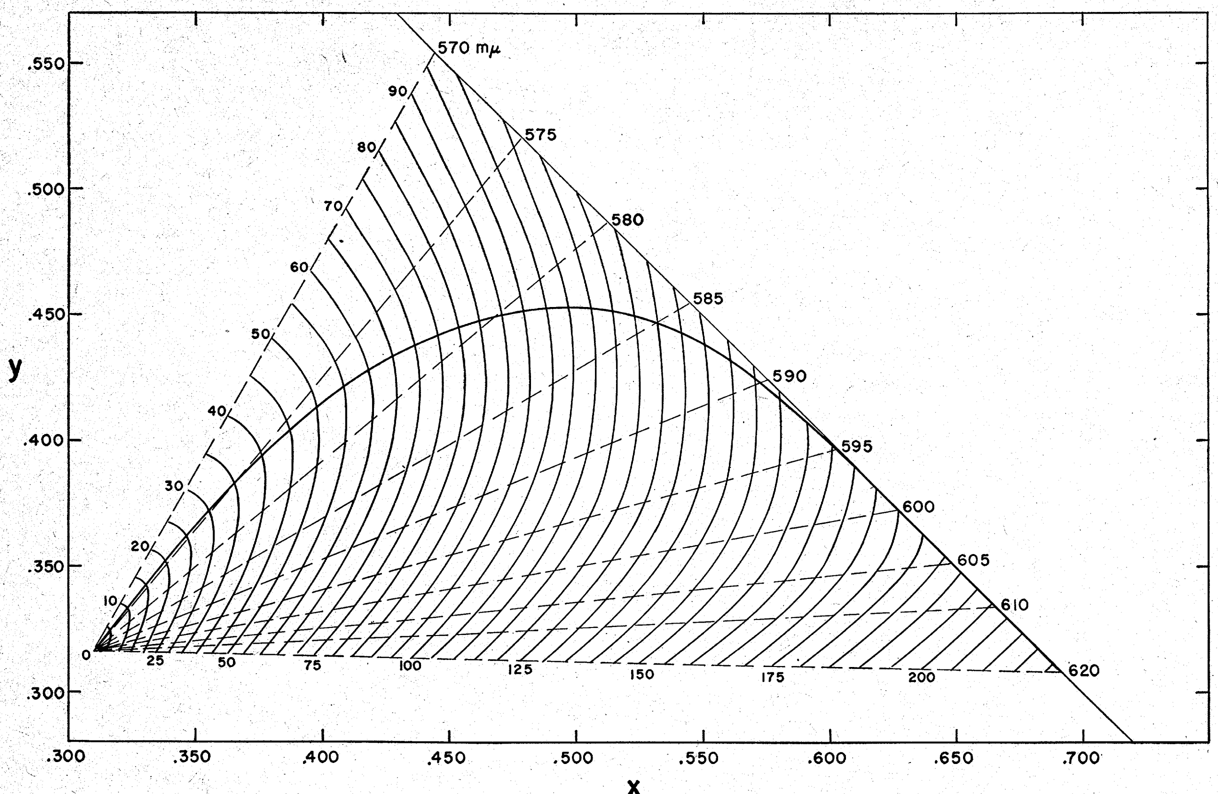

FIG. 3. Loci of points along lines of constant dominant wavelength that depart from "colorless" by 5, 10, 15, ⋯ 220 MacAdam units of chromaticity difference. The average locus of chromaticities of sugar products is also shown.

Comparisons of sample and standard chromaticities should be made at constant luminance. This can be accomplished in a rough way by moving nearer to an artificial diffuse source of white light for comparisons in the medium and dark range of chromaticities.

A third method of determining ΔS for a given sugar solution is available through correlation with absorbancy data at selected wavelengths for solutions of negligible turbidity. Tentative correlations are shown in Fig. 4 from data on liquid sugars (thickness 100 mm, with clear colorless glass as reference) and on caramel-glycerin solutions (31.5 mm, reference, glycerin). Values of ΔS were determined graphically (Fig. 3) since chromaticity coordinates were known. The entire range of chromaticities is covered by use of 420 mμ for light-colored products, 560 mμ for medium-colored products, and 720 mμ for dark products. These are the wavelengths commonly used in the sugar industry for evaluating the color of sugar solutions absorptiometrically. The curves are not linear but the relationships are systematic.

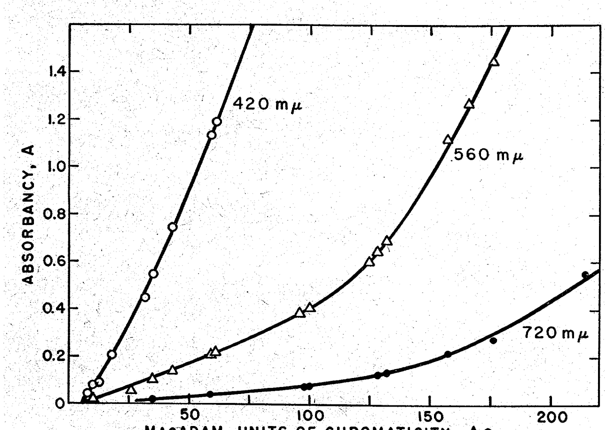

FIG. 4. Relationship between absorbancy at selected wavelengths and MacAdam units of sugar chromaticity for solutions of sugar products having negligible turbidity.

A comparison of MacAdam units of sugar chromaticity and NBS units of sugar color[5] is made in Table IV by means of data on some of the glass color standards of Table I. The NBS units are calculated with and without the "darkness" term $[0.23(10-V_y)]^2$ of the Adams equation, i.e., for total color and for chromaticity only; also with the recommended conversion factor[12] $f=50$ and with an arbitrarily selected factor $f=46$. The following conclusions are drawn from these data. (1) There is little difference, at least for the lighter colors, between ΔE_{NBS} for total color and for chromaticity. (2) For the lighter colors up to at least 60 units, the two chromaticity scales ΔS and ΔE_{NBS} agree within about 10% and can be made to coincide for all practical purposes by choosing $f=46$ in the Adams equation.

(3) For the medium and dark colors above about 80 units, the ΔE_{NBS} scale breaks down, both for total color and for chromaticity. This is beyond the range used by Deitz for ΔE_{NBS}, which was about 0–70 units. This limitation could probably be overcome by a method of calculation involving increments. The MacAdam scale of sugar chromaticity does not have this limitation and hence has the present advantage of greatly extended range, about 0–220 units. Neither scale should be regarded as perfect from the viewpoint of uniform perceptibility, but it is gratifying that they agree well in the range of lighter colors.

TABLE III. Intersections of MacAdam 5× loci with average sugar products locus. Description of glass standards with chromaticity coordinates near the intersections.

Intersections with sugar products locus: MacAdam units ΔS	x	y	Glass standards along sugar locus: Glass type[a]	Glass thickness mm	Test λ $m\mu$	Test standard[a]	T/T_s
0	0.3101	0.3163	clear	...	...	...	...
5	0.3163	0.3248	(1)	0.61	429	WW(*ls*)	1.46
10	0.3231	0.3338		1.12			1.31
15	0.3303	0.3429		1.64			1.16
20	0.3380	0.3522		2.36			1.00
25	0.3462	0.3622	(2)	1.44	454	WW(*h*)	1.67
30	0.3550	0.3720		1.84			1.47
35	0.3650	0.3831		2.26			1.29
40	0.3759	0.3939		2.66			1.10
45	0.3870	0.4040		3.08			0.91
50	0.3976	0.4132		3.50			0.73
55	0.4080	0.4211	(3)	1.10	481	EW(*h*)	1.11
60	0.4177	0.4274		1.24			0.99
65	0.4267	0.4328	(4)	1.30	521	W(*h*)	1.58
70	0.4357	0.4373		1.42			1.48
75	0.4449	0.4412		1.55			1.39
80	0.4539	0.4449		1.69			1.29
85	0.4624	0.4478		1.84			1.20
90	0.4710	0.4500		2.06			1.10
95	0.4798	0.4517		2.20			1.00
100	0.4882	0.4527		2.37			0.91
105	0.4970	0.4530		2.60			0.81
110	0.5054	0.4528		2.86			0.71
115	0.5146	0.4514		3.15			0.62
120	0.5231	0.4496	(5)	1.72		ELA(*h*)	1.09
125	0.5321	0.4468		1.90			0.993
130	0.5412	0.4430		2.10			0.883
135	0.5508	0.4384		2.32			0.777
140	0.5607	0.4322		2.60			0.667
145	0.5700	0.4250		2.90			0.564
150	0.5803	0.4163		3.23		LA(*h*)	1.44
155	0.5908	0.4066		3.62			1.32
160	0.6011	0.3971		4.06			1.19
165	0.6097	0.3888		4.58			1.06
170	0.6188	0.3804		5.18			0.923
175	0.6273	0.3720		5.92			0.787
180	0.6362	0.3632		6.80			0.650
185	0.6452	0.3542	(6)+(7)	1.15[b]	578	A(*h*)[c]	1.85[c]
190	0.6518	0.3474		1.30			1.65
195	0.6580	0.3415		1.43			1.45
200	0.6642	0.3353		1.56			1.25
205	0.6700	0.3293		1.70			1.05
210	0.6760	0.3234		1.84			0.85
215	0.6822	0.3176		1.97			0.65
220	0.6882	0.3116		2.10			0.45

[a] See Table I.
[b] Thickness of smoke component, type (7).
[c] Cherry component only, type (6).

TABLE IV. Comparison of NBS units of sugar color, ΔE_{NBS}, with MacAdam units of sugar chromaticity, ΔS. Comparisons are valid only for the lighter colors above the spacing.

Glass standard	ΔE_{NBS} Total color[a]	ΔE_{NBS} Chromaticity only $f=50$	ΔE_{NBS} Chromaticity only $f=46$	ΔS MacAdam units of chromaticity
WW(*ls*)[b]	23.3	21.8	20.1	20.2
W(*ls*)	46.3	44.3	40.8	40.4
WW(*h*)	49.7	46.8	43.0	42.7
EW(*h*)	67.7	65.0	59.8	59.6
W(*h*)	95.2	90.6	83.4	94.7
LA(*ms*)	100	95	87	104
ELA(*h*)	114	105	97	125
MA(*ms*)	121	110	101	138
DA(*ms*)	112	85	78	162
LA(*h*)	113	86	79	167
A(*h*)	111	48	44	206

[a] See references 5 and 12 (page 267).
[b] See Table I for identification.

With either scale the thickness of solution or liquid viewed must be specified. Deitz[5] has shown that below 40 units ΔE_{NBS} is proportional to thickness of sugar solution viewed, permitting predictions of color of mixtures of sugar liquors (if pH and concentration of sugar solids is held constant); also that in this range ΔE_{NBS} is proportional, within ± 2 units, to attenuancy at 420 $m\mu$. The same should be true of the MacAdam scale of sugar chromaticity in this range, although close linearity is not indicated in Fig. 4. This property is very useful but is likely coincidental and cannot be expected to hold over a wide range. For example, in selecting the color standards for sugarcane molasses and a practicable viewing thickness of product, it was found that in the range $\Delta S = 117$ to 220 a reduction of viewing thickness from 0.125 to 0.100 in. (a 20% reduction) resulted in a shift of ΔS amounting to approximately 6%.

It could be argued that all chromaticities in the medium and dark range could be shifted to values of 70 units or less, where both scales agree, by choice of thinner cells or by dilution with "colorless" sugar solution of the same pH and concentration of sugar solids. Although this can be done in many cases, it would be inconvenient and impractical, at least for purposes of official classification, for such dark products as sugarcane sirup and sugarcane molasses.

The MacAdam single-number scale of sugar chromaticity has the advantages of covering the entire gamut of sugar chromaticities, determination of scale number from chromaticity coordinates rather than from tristimulus values, and of representation by a series of glass standards spaced at intervals of five units on the scale. By means of correlations such as those shown in Fig. 4 and Table IV, other scales in use by the sugar industry could be compared or converted to a single scale of fundamental meaning. The 45 glass standards spaced uniformly on this scale would likely not be practicable for general use because of the difficulty in reproducing them. However, selected glasses in the series, or any one of the well-characterized USDA glass color standards, might have practical application in the sugar industry, for example, in control work where color limits or reference points in simplified visual methods are needed. Another potential use for the MacAdam scale and this series of glasses is in the selection or the revision of glass color standards for various sugar products. It is obvious from an examination of Table I that a uniform or systematic spacing was not achieved in any of the USDA glass color standards for sugar products, except in the experimental standards for liquid sugar. This is because spacings were established arbitrarily many years ago and were not readjusted when glass color standards were devised to replace previous standards. Examples in other commodities for which transparent standards were revised to achieve a systematic visual spacing are the USDA color standards for rosin[16] and the Union Colorimeter scale for lubricating oil and petroleum.[17]

ACKNOWLEDGMENTS

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[16] B. A. Brice, J. Opt. Soc. Am. **30**, 152 (1940).

[17] Judd, Plaza, and Belknap, J. Research Natl. Bur. Standards 44, 559 (1950).